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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
CORADCOM-79-0786-2

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COMMUNICATIONS - ELECTRONIC INTRASYSTEM ELECTROMAGNETIC INTERFERENCE MEASUREMENT TECHNIQUES AND INSTRUMENTATION

Lester E. Polisky et.al.
ATLANTIC RESEARCH CORPORATION
5390 Cherokee Avenue
Alexandria, Virginia 22314

February 1980

Quarterly Report for Period 21 September 1979 -
21 December 1979

Approved for public release: Distribution unlimited

Prepared for: CENCOMS

CORADCOM
US ARMY COMMUNICATIONS RESEARCH & DEVELOPMENT COMMAND
FORT MONMOUTH, NEW JERSEY 07703

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents the results obtained during the second quarter of the Communications-Electronics Intra-System Electromagnetic Interference Measurement Techniques and Instrumentation Project. The period covered was 21 Sept.1979 to 20 Dec.1979. The major efforts in the second quarter consisted of completing the IEMCAP feasibility study and developing a broadband measurement system for conducting EMC measurements.

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Table of Contents

1. INTRODUCTION

This is the second of three quarterly reports that will be submitted under this contract. A final report will be submitted at the end of the fourth quarter. Each of the quarterly reports will describe the work accomplished and the progress of the program in the quarter with special discussion reserved for any problem areas and proposed corrective actions for these problem areas.

The purpose of this contract is to develop an improved approach to the communication-electronic system integration problem from an EMI standpoint. Specifically, the effort is investigating the use of computerized analytical tools such as IEMCAP in conjunction with the overall EMI test procedures of MIL-STD-461A and 462 to develop a more meaningful and economical approach to defining the system EMI problems. The analytical techniques shall provide guidance and insight into the system characteristics that will allow for effective utilization of measurement resources and time. The contract results will lead to the establishment of an interactive EMI/EMC analysis and measurement procedure that will provide the basis for a meaningful EMI intrasystem measurement standard. In pursuit of the contract goals, this quarterly report contains the results of the IEMCAP feasibility study and the development of a hypothetical broadband measurement technique for emissions that would be compatible with an associated analytical technique.

This is a four section report. In addition to this introductory section, Section 2 describes second quarter events, Section 3 describes the work accomplished in the second quarter and Section 4 describes the work planned for the third quarter of the project.

2. SECOND QUARTER EVENTS

Second quarter events included a meeting with Stuart Albert, USACORADCOM project engineer, at Atlantic Research on 5 October 1979 and concentrated technical effort in two major project areas. They were the completion of the IEMCAP feasibility study and the initiation of the development of a broadband measurement technique for emissions.

The 5 October meeting provided an opportunity for the USACORADCOM project engineer and Atlantic Research project personnel to review the techical goals for the project, discuss administrative requirements of the project contract, critique and discuss the content and scope of the first quarterly report and future reports, and to examine the automated test equipment setups at the Atlantic Research Corporation TEMPEST EMI/EMC facility.

The IEMCAP feasibility study was completed at the end of the second quarter and the conclusion reached is that IEMCAP is a viable analysis tool that can be utilized to make EMI/EMC testing of systems more efficient. Work now being performed on IEMCAP under other programs is expanding the capability of the program to include frequencies above 18 GHz, more geometries and peak as well as average power emissions. The other programs are under United States Air Force Contracts and are: IAP Surface Geometry Generation, Contract Number F30602-77-C-0126; IEMCAP PRE/POST Processor, Contract Number F30602-77-C-0146; IAP Structure Design Study, Contract Number F30602-77-C-0150; and Current IAP Model Improvement, under Contract F30602-77-C-0169. A discussion of IEMCAP as applied to EMI/EMC Testing is presented in Section 3 of this report.

A broadband measurement technique to be used in conjunction with IEMCAP to streamline EMI/EMC testing is presented in Section 3 of this report. The technique deals with emissions only. An attempt has been made to identify hardware and describe parameters such as noise level, sensitivity and dynamic range for the proposed setups. A comparision to present MIL-STD-461 limits is also presented. The main problem with the proposed broadband measurement technique is in the dynamic range area. A continuing effort will be made to resolve this problem and to further expand the broadband technique in both scope and frequency range.

3. WORK ACCOMPLISHED IN THE SECOND QUARTER

a. IEMCAP Feasibility Study Results

An IEMCAP feasibility study was performed. The study included an indepth look at the input data requirements for IEMCAP, limitations of the present program, and applicability of IEMCAP for analyzing the EMC of a given system. The input data required for IEMCAP does not appear to be overly excessive in terms of the amount of data required to perform a system EMC analysis. However, some of the required data, e.g., out-of-band emissions and susceptibilities, or wire type and routing, may be difficult to obtain in the early stages of system development and thus there remains a questionable area that must be resolved. Also, a data collection philosophy needs to be established for Army system procurements.

There are several limitations associated with the present IEMCAP. These limitations in the program may be considered as resulting from the following:

- State-of-the-Art Modeling Capability
- Stringent Computer Requirements
- Air Force Systems Requirements

Overall the program limitations are as appropriate to applying IEMCAP to Army systems as they are to Air Force systems. However, it is recognized from this study that some modifications of the IEMCAP are necessary for handling Army systems. Modifications considered to date consist of the following:

- System Geometry Structure
- Antenna Coupling Models which Account for Diffraction and Shading Factors Associated with Army Structures
- Specification Generation Philosophy

The overall result of the IEMCAP feasibility study to date is that the IEMCAP should be used as an integral part of the overall test procedure. Further study beyond this point is required in the following areas:

- Philosophy For Using the IEMCAP
- Data Collection with Regard to Army System Procurements
- Other possible modifications to IEMCAP to make it more efficient for use by the Army

Some of the questions and problems associated with the above efforts will require inputs from Army personnel, and possibly, some actual experience on implementing the IEMCAP on an Army system will be required to provide the answers.

(1) Definition of Equipment Parameters Data Needed for IEMCAP Inputs

IEMCAP is designed to perform an EMC analysis on a system throughout the various stages of the system's life cycle from conceptual studies of new systems to field modification on existing systems. To accomplish this task, the IEMCAP generates system data base which can be continually maintained and updated to follow system design changes/modifications. Initial inputs to the data base must be provided by the user. The input data base structure is shown in Figure 1. As shown by the figure, there are four basic levels in the hierarchical structure which are the following:

- System
- Subsystem
- Equipment
- Port

The IEMCAP definition for each of these levels is as follows:

System. The system data defines the system type (aircraft, spacecraft, ground), overall physical dimensions, coordinate system parameters, and basic analysis parameters applying to the entire system. It also includes common model parameter tables. These tables contain basic parameters for apertures, antennas, filters, and wire characteristics which have multiple use throughout the system. They are referenced at the port level so that the basic parameters are specified only once. For example, a particular antenna type may be used for several different ports in the system. The antenna physical dimensions, main beam shape, gain, etc. are specified in the system data along with an identifying name. In the port data, this name is referenced, and only the antenna coordinates and main beam orientation are specified for each of the ports using the antenna.

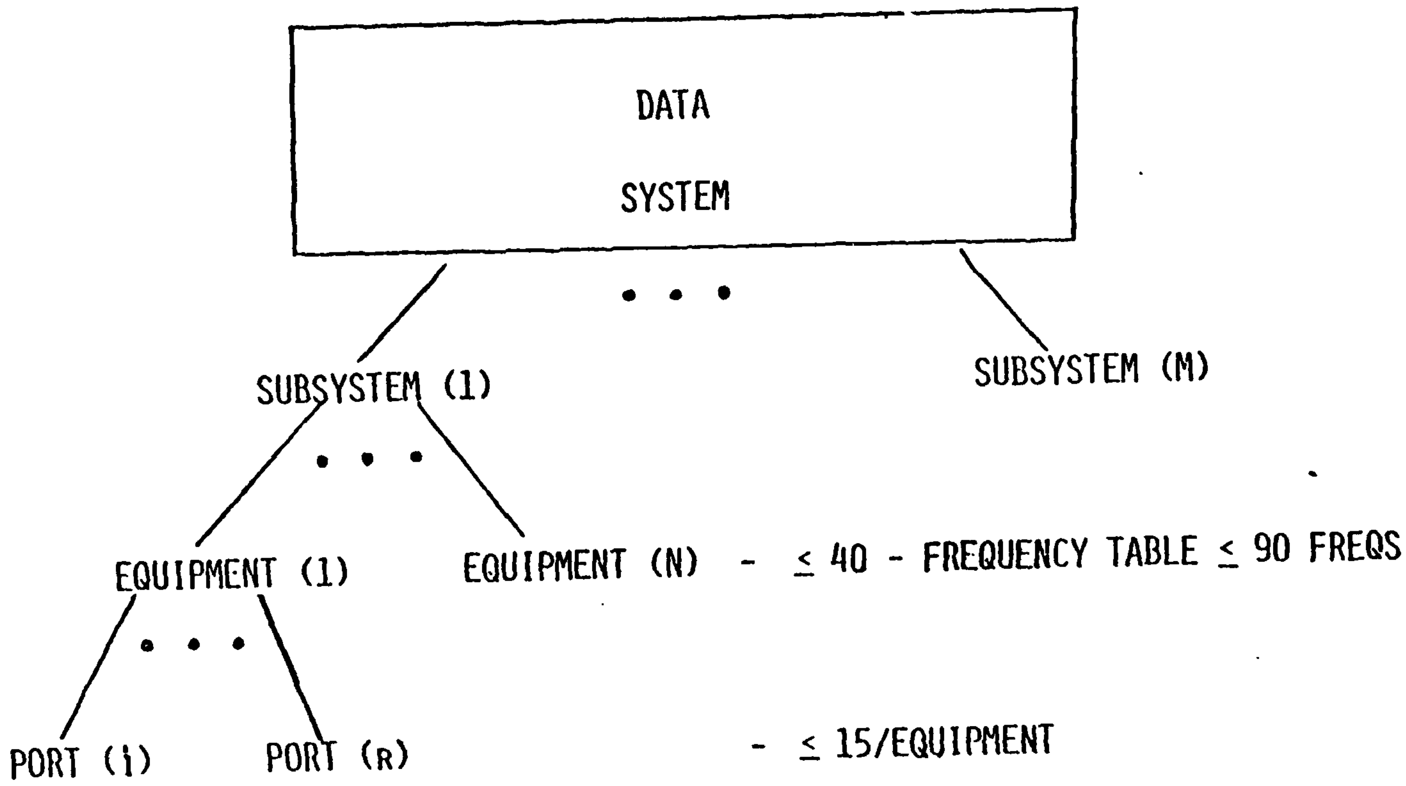

Figure 1. Data Base Structure.

Subsystem. A subsystem consists of well defined parts of a system usually performing a related task. A radar package and a central computer complex are examples of subsystems. This level is defined for convenience in organizing the data and is not a functional level within the program. Hence, equipments need not be specified with reference to a subsystem. A minimum of one subsystem must be identified.

Equipment. An equipment is a physical box located in the system, such as a transmitter unit.

Port. A port is a point of entry or exit of electromagnetic energy from an equipment. A port may be connected to an antenna or to a wire. Leakage into and out of the equipment case is also a port. A port may be designated as a source (emitter), a receptor, or both. The analyses are performed on a port-to-port basis. All ports within the same equipment are assumed compatible with each other.

In addition to the above data the wire bundle data is also organized into a heirarchy, which allows complex wire routines to be analyzed. The components are as follows:

Bundle. A bundle is a group of wires which, for some portion of their lengths, run parallel to each other.

Bundle point. A point in the system at which a bundle branches or changes direction. Between bundle points wires are assumed to run in straight lines, and no branching occurs.

Segment. A segment is a section of a bundle running between points. Segments are designated by giving the bundle points. Within a segment the wires are assumed to run parallel. A segment may also run by a dielectric aperture and be exposed to energy from external antennas and environmental electromagnetic fields.

Wire. A wire connects two or more ports. Its routing is specified by designating the bundle points through which it passes for which segments have been defined. The wire physical parameters are given by referencing the Wire Characteristics Table, which is specified at the system level.

The remainder of this subsection will discuss the system, subsystem, equipment and port requirements and wire routing in more detail.

(a) System Data

The system data defines certain physical aspects of the system and specifies basic analysis parameters applying to the entire system. The basic systems appropriate to IEMCAP are aircraft, spacecraft and ground systems. The parameters required to identify each of these systems is given below

- AIRCRAFT - Conical nosed cylinder with wings. A flat or round bottom cylindrical model may be used to approximate the vehicle shape. Radii associated with the cylinder and conical sections are required input data. Wingroot and wingtip coordinates must be provided.
- SPACECRAFT - Same as aircraft but without wing parameters.
- GROUND - A ground station such as a hut, or other collection of ground based communications-electronics systems. This system is associated with a finitely conducting ground plane and the conductivity (σ) and relative permittivity (ε_r) must be specified.

Any convenient coordinate system may be used for the above. However, the IEMCAP User's Manual suggests that for aircraft coordinates use the commonly accepted aircraft system of butt line, water line and fuselage station. For spacecraft and ground systems use the rectangular (x, y, z) coordinate system.

Another input option available at the system level provides for identifying an ambient electromagnetic field environment for the system. The ambient field levels may be specified both external and internal to the system. Wires exposed by apertures in the system structure and antennas are exposed to the external fields. Equipment cases and wires inside the system are exposed to the internal fields. Either the external or internal fields or both may be specified. If the external field only is specified, the internal field defaults to 40 dB less than the external field. If the internal field only is specified, the external field defaults to 40 dB greater than the internal field. If neither field is specified, the default value is zero and no environmental field calculations are performed.

As indicated above, there are certain common model parameters specified at the system data level. This data specifies parameters for apertures, antennas, filters and wire characteristics used throughout the system. Basic parameters must be identified for each aperture antenna, filter and wire associated with the system. An aperture is defined at any non-metalic opening (symbolic or actual) in the structure in which EM coupling to a wire(s) is to be considered. Apertures expose wire bundle segments to external electromagnetic energy from antennas and any defined environmental fields. The required aperture parameters are aperture identification code, coordinates of the center of the aperture, width and length of the aperture and location on the structure if it is an aircraft.

Antenna common model parameters are a function of the antenna type. Antennas for IEMCAP purposes are categorized as low, medium and high gain. The low gain antenna types consist of the dipole, whip, slot and loop. The specific medium and high gain antennas identified for the IEMCAP are parabolic dish, log periodic, horn, phased array and spiral. However, a user may model any antenna via the medium/high gain model by using one of the model codes for the above antenna types as a pseudo model. Each antenna in the system must be identified by a code, IEMCAP model, primary polarization and appropriate physical dimensions. Antenna gain parameters are required input data for the medium and high gain antenna types. Each of these parameters are defined below:

- antenna length (low gain)
- largest antenna dimension
- design frequency maximum antenna gain
- 3-dB vertical beamdwidth of the main beam
- 3-dB azimuthal beamwidth of the main beam
- major sidelobe gain
- major sidelobe beamwidth
- backlobe gain

The above data provides for a three dimensional three-sector representation for the medium and high gain antennas. The three sectors correspond to the antenna mainbeam, major sidelobe and backlobe regions. A two sector representation may be specified by defining the mainbeam characteristics and the major sidelobe region. The major sidelobe gain and beamwidth are specified such as to encompass all but the mainbeam region of the antenna.

The filter common model parameters are a function of the prestored models. The prestored filter models consist of a single tuned stage, transformer coupled stage, Butterworth tuned, low pass, high pass, band pass and band reject. The required input data for each model is a filter identification code, and the type and data as defined below:

- Single tuned stage
  - tuned frequency
  - bandwidth
  - insertion loss
  - maximum isolation
- Transformer coupled stage
  - tuned frequency
  - insertion loss
  - maximum isolation
  - circuit Q (quality factor)
  - circuit coupling factor (m)
- Butterworth tuned
  - tuned frequency
  - bandwidth
  - maximum isolation
  - insertion loss
- Low pass
  - upper break point frequency
  - insertion loss
  - maximum isolation
- High pass
  - lower break point frequency
  - insertion loss
  - maximum isolation

- Band pass and Band reject
  - lower break point frequency
  - upper break point frequency
  - insertion loss
  - maximum isolation

The above models represent filters as ideal, lossless networks, made up of only reactive elements (capacitors and inductors). When a filter is used in a circuit, however, it "sees" an input impedance at the source end and an output impedance at the load end, both of which contribute to the overall transfer function between source and load. In the absence of a filter, the maximum power is delivered to the load when the load impedance matches the source impedance. For equal source and load resistances, the maximum power delivered to the load is half the total power, the other half being dissipated in the source resistance. The insertion of a filter between the source and load selectively attenuates the signal delivered to the load at a given frequency.

The filter transfer models calculate the "insertion loss" in dB provided by a filter at a given frequency, i.e., the reduction in delivered power due to insertion of a filter. Thus the insertion loss of the single tuned filter at the resonant frequency is 0 dB, i.e., the insertion of the filter does not attenuate the signal delivered to the load at that frequency.

Practical filters are not ideal, lossless networks; there are always dissipative elements which affect filter performance. Consequently the filter models provide for a minimum insertion loss to represent actual dissipation at the tuned frequency or in the pass band. The filter models also provide a maximum insertion loss or isolation to represent the departure from the ideal rejection in the rejection band. The minimum and maximum insertion loss provide lower and upper bounds for the filter transfer function.

The wire common model parameters consists of a table of general wire characteristics which are referenced for specific wires in a given wire bundle. The wire characteristics table was designed to be applicable to general systems to work in conjunction with the models for computing coupling between circuit pairs even when the connecting wires have a relatively complex configuration (such as shielded, twisted pairs). For the IEMCAP, the circuits for which models have been developed include:

- Single (unshielded) wires with ground return
- Twisted pair circuits (balanced or unbalanced)
- Shielded wires (single or double shield) with single or multiple grounded shields
- Shielded twisted pair circuits (balanced or unbalanced, single or double shield) with single or multiple grounded shields.

These models are valid for both emitter and receptor circuits and any type of emitter circuit may be analyzed with any type receptor circuit. The input data for the above wire types includes a wire type identification code and the data corresponding to the wire types as defined below.

- Unshielded Wires
  - conductor diameter
  - conductor conductivity
  - insulation thickness
  - insulation dielectric constant
  - twisted pair or single wire
- Single Shielded Wires
  - conductor diameter
  - conductor conductivity
  - insulation thickness
  - insultation dielectric constant
  - shield interval diameter
  - shield thickness

    - shield jacket thickness
    - shield-to-conductor capacitance
    - twisted pair or single wire
- Double shielded wires (shields are separated by dielectric)
    - conductor diameter
    - conductor conductivity
    - insulation thickness
    - insulation dielectric constant
    - inner shield internal diameter
    - inner shield thickness
    - inner shield jacket thickness
    - shield-to-conductor capacitance (to inner shield)
    - outer shield internal diameter
    - outer shield thickness

(b) Subsystem Data

The subsystem identification is the second level of the hierarchical structure which exists in the IEMCAP data base structure. The subsystem level provides a means for organizing groups of equipments performing related tasks. For example, an aircraft system might have a navigation subsystem which is composed of several equipments such as a transmitter-receiver-unit, a display unit, and a navigation computer. For IEMCAP purposes this navigation subsystem should be identified by an identification code with the physical boxes comprising the subsystem defined as equipments. Other subsystems within the aircraft would be defined in a similar manner.

The IEMCAP requirements stipulate that at least one subsystem must be provided for a given system. More than one subsystem is allowed per system and the program user has total control over the number of subsystems to use.

The only input data requirement for the subsystem level is an identification code.

(c) Equipment Data

For IEMCAP purposes, the physical boxes comprising a subsystem are defined as equipments. Equipment data is represented as the third level in the hierarchical input data structure. This level of input data provides specific parameters which pertain to the overall equipment characteristics. The data identified at the equipment level are used at the port source and receptor level.

Each equipment within a subsystem must be assigned an identification code, MIL-STD specification, compartment identification code, security classification, coordinates and fixed or adjustable EMC limits. The equipment identification codes are user assigned and must be unique within a given subsystem. The MIL-STD Specifications are prestored models in IEMCAP and an option of MIL-STD-461A (Notice #3) or MIL-I-6181D is currently available.

Each equipment in a system must be assigned a compartment identification code. IEMCAP uses the equipment compartment identification to ascertain case-to-case (box-to-box) coupling calculations. Only equipments with identical compartment identification codes are considered for case-to-case coupling computations. Therefore, at least one compartment must be specified for a system. However, the user may elect to have the program omit the case-to-case calculations between isolated equipments within the system by assigning them to different compartments.

The locations of the equipment within the system is determined by specifying the coordinates of the center of the physical box representing the equipment. The units for the equipment coordinates are the same as those described in Section (a).

For each equipment in a system, an option of fixed or adjustable EMC limits is provided. If the option to adjust the EMC limits is chosen, the nonrequired port spectra are adjustable by the specification generation routines to the limit defined at the port source or receptor level. If fixed EMC limits are used, then none of the equipment port spectra are adjusted. This parameter is ignored for all IEMCAP execution options except the specification generation run.

In addition to the above equipment input parameters, a spectrum sample frequency table must be defined for each equipment in the system. This equipment frequency table is applicable to all port spectra within a given equipment. The equipment frequency table may be defined by default values, user inputs or a combination of default and user inputs. The input parameters for the equipment frequency table are

- lowest frequency to be considered (default 30 Hz)
- highest frequency to be considered (default 18 GHz)
- number of frequencies per octave (default = 3)
- maximum number of frequency $\leq$ 90 (default = 90)
- user specified frequency in ascending order $\leq$ 88 (must be at least two less than the maximum number of frequencies specified)

(d) Port Data

The physical boxes comprising the subsystem are defined as equipments electromagnetic energy may enter or leave these equipments via ports. Ports are designated as emitters or receptors or both. An emitter port generates electromagnetic energy and a receptor port is susceptible to electromagnetic energy. Ports within an equipment are assumed compatible with each other. Ports may exist in an equipment as intentional or unintentional. An example of an unintentional port is leakage into or out of an equipment case. An example of an intentional port is a connector pin through which AC power, signals, etc. are brought into or out of the equipment. Such ports are connected to wires or antennas. The port input data for wire and antenna connected ports consists of port identification codes and the following:

- Wire Connected Port
  - Wire bundle identification
  - Wire identification code
    (same as system level identification)
  - Bundle point identification
  - Return path of signal
  - Shield termination
  - Aperture exposed wire
  - Termination resistance
  - System displacement factor for source
  - System displacement factor for receptor
  - Filter identification code
    (Same as system level identification)
- Antenna Connected Port
  - Antenna identification code
    (Same as system level identification)
  - Direction of mainbeam peak
    (Vertical angle)
  - Direction of mainbeam peak
    (Azimuth angle)
  - Antenna coordinates
    (Center of antenna in same units
    as specified in Section (a)
  - Antenna location on wing if system is an aircraft
  - Termination resistance
  - System displacement factor for source

- System dispalcement factor for receptor
- Filter identification code
  (Same as system level identification)

To complete the port specification input data a port must be designated as a source, receptor or both and additional data specified as a function of port type. IEMCAP models the following port types

- Radio frequency
- Power
- Signal
- Control
- Electro-explosive devices
- Equipment case

The specific data required for each port type is shown below.

- Radio Frequency Port
  - Adjustment limit displacement from the initial spectrum level. The Specification Generation Routine(SGR) can adjust the spectrum this number of dB from its initial amplitude. Must be positive.)
  - Lowest carrier frequency*
  - Highest carrier frequency*
  - Minimum sensitivity (receptor)
  - Bandwidth of Channel
  - Modulation/signal code
    - Continuous wave
    - Pulse duration modulation
      - Pulse repetition
    - Non Return to Zero(NRZ)pulse code modulation
      - Pulse repetition
    - Biphase pulse code modulation
      - Pulse repetition
      - Modulation index

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* Note lowest carrier = highest carrier frequency provides tuned frequency carrier condition.

- Pulse position modulation
  - Pulse repetition
  - Pulsewidth
- Conventional telegraph
  - Words per minute
  - Tone frequency
- Frequency-shift keying
  - Pulse repetition
  - Difference between upper and lower oscillator frequencies
- Pulse amplitude modulation
  - maximum frequency deviation
- Radar (pulsed RF)
  - Rectangular
  - Trapezoid
  - Cosine squared
  - Gauss
  - Chirp
  - Pulse parameters required
  - Pulsewidth
  - Rise time
  - Fall time
  - Pulse compression ratio (neg. if frequency deviation is negative
- Amplitude modulation
  - Double side band suppressed carrier
  - Single side band, lower
  - Single side band, upper
  - Frequency modulation
  - Local oscillator leakage from receivers
    - Signal type code
      - Voice
      - Clipped voice
      - Telegraphy digital

    - Harmonic displacement level (source) relative to fundamental for the 2nd, 3rd, ... up to 10th
- Power Port
    - Adjustment limit displacement from initial spectrum level
    - Voltage (RMS) of line
    - Frequency (0 if DC)
    - Highest harmonic
    - Number of phases
    - Ripple or noise spectrum
- Signal and Control Ports
    - Spectrum adjustment limit displacement from initial spectrum level
    - Lowest required frequency
    - Highest required frequency
    - Modulation/signal code
        - Pulse duration
            - Pulse repetition rate
        - Nonreturn to zero pulse code modulation
            - Pulse repetition rate
        - Biphase pulse code
            - Pulse repetition rate
            - Modulation index
        - Pulse position modulation
            - Pulse repetition rate
            - Pulse duration
        - Morse telegraphy
            - Word per minute
            - Tone frequency

- Pulse amplitude modulation
  - Pulse repetition rate
  - Pulse duration
  - Exponential decay spike
    - Pulse repetition rate
    - Pulse duration
  - Rectangular
    - Pulse repetition rate
    - Pulse duration
  - Trapezoidal pulse train
    - Pulse repetition rate
    - Pulse duration
  - Triangular rise time
    - Pulse repetition rate
    - Pulse deviation
  - Sawtooth
    - Pulse repetition rate
    - Pulse duration
  - Damped sinusoid
    - Pulse repetition rate
    - Oscillatory frequency of damped sinusoid
    - Decay frequency of damped sinusoid
    - Voice
    - Clipped voice
  - Amplitude (volts, amps)
  - Units code
  - Bandwidth of information

- Electro-explosive device port
  - Adjustment limit
  - Maximum power for no fire
  - Maximum current for no fire
- Equipment Case Port
  - Spectrum adjustment limit displacement from initial spectrum level
  - Narrowband specification spectrum
  - Broadband specification spectrum

For all of the above port types the modulation/signal parameter may be specified as user input. That is, the user may specify up to ten frequency/amplitude point pairs to use in lieu of the prestored modulation models.

(2) Limitations of IEMCAP Program

The system approach of the IEMCAP involves identifying all ports in the system having potential for signal coupling. These ports are categorized as emitters and receptors with associated signal coupling paths. Since the function of the IEMCAP is to determine, by linear analysis,(no nonlinear effects such as desensitization, intermodulation etc. are computed by IEMCAP) whether signals from one or more emitters unintentionally coupling to a receptor will impair the receptor's required operation, it is necessary for the system model to include some characterization of the receptor's performance degradation due to interference signals. The IEMCAP assumes that average power of signals is the criterion appropriate for assessment of an interference condition in receptors.

The assumption in the IEMCAP system model that receptors are power vulnerable devices implies that their performance can be characterized in terms of average power of signals present at their input. The result of integration of signal power spectral densities is some power level at the receptor's detector which may or may not exceed a threshold power level defined for that receptor. This total power level at a receptor's detector will, in general, be a composite of desired signal power, thermal noise power and system induced interference power.

In order to simulate the physical operation of actual power vulnerable receptors the IEMCAP includes a routine for mathematically integrating the interference power spectral density present at a receptor's input, weighted by the receptor power transfer function, in its assessment of the interference power level at the receptor's detector. The model forms the ratio of this computed interference power level with the tolerable interference power level assigned to the receptor. This interference power ratio is called the "integrated EMI margin (I.M). When expressed in decibels, a positive I.M. is considered an interference condition while a negative I.M. is generally considered a compatible condition.

A further aspect of the IEMCAP system model that needs discussion is the manner in which broadband emission spectra are treated in the program. The integrated EMI margin is evaluated by a weighted integral of an emitter's power spectral density in watts per hertz received at the input port of a receptor. Broadband emission limits, however, are not specified in terms of power spectral density but in terms of the quantity measured by a standard EMI test receiver, such as an Empire Devices NF-105; namely, the current spectral level in microamps per megahertz. The current spectral level is a measure of the peak current contained in the instrument bandwidth.

There are some receptors in systems, being utilized more as technology advances, that are not adequately represented by the power vulnerability assumed in the IEMCAP system model. These threshold vulnerable devices must have more information about their actual modes of excitation and the IEMCAP should make provisions for an option capable of predicting the system effects on such devices. An approach to providing the IEMCAP with a logical alternative analysis using peak current margins, for threshold devices is presently being evaluated in another program. A key aspect remaining to be adequately treated is the proper assignment of susceptibility levels for such devices. There appears currently to be a lack of consensus in the electronics community about the degree of vulnerability to these types of system elements to EMI.

During the calculation of the coupling from emitter ports to a particular receptor port, a check is made to determine if any wires connected to any of the emitter ports are in the same bundle (no bundle-to-bundle coupling in IEMCAP) and run as wires connected to the receptor port. If there are such wires, the wire-to-wire coupling routine is called. This routine computes the spectral voltages induced in the receptor circuit by the emitter circuit. These calculations are performed on a pair basis (only one emitter circuit considered to couple with the receptor circuit for each calculation) with the effects of all other circuits neglected during this calculation. Each possible pair coupling is computed in turn and the total coupling is calculated by summing all of the pair couplings without regard to phase. It should be noted that the validity of this wire-to-wire coupling model has been verified by experimental data.

For frequencies where the wire length is short compared to a wavelength, the models provide an accurate representation of the actual coupling situations. However, for the frequencies where the wire lengths are comparable to or greater than the wavelength, the actual coupling is very sensitive to line length and no simple model is available for modeling the exact coupling. In this frequency range, the models approximate the envelope of the coupling curve so that the predicted coupling is never less than the actual.

The basic model for wire-to-wire coupling considers capacitive coupling due to the interwire capacitance and inductive coupling due to the mutual inductance between the wires. This model uses the approximation that the total coupling can be computed as the sum of the capacitive and inductive coupling computed separately.

The basic antenna model for medium and high gain antennas is a three sector representation corresponding to a main-beam, major sidelobe and backlobe. Each sector subtends a solid angle in the unit sphere and has an associated quantized antenna gain. This representation of an antenna is specified for the designed frequency and all locations associated with a given antenna. That is, the IEMCAP assumes that antennas are frequency independent and the placement of the antenna on the structure does not distort the radiation characteristics. Polarization effects are neglected in the antenna coupling calculations.

The intravehicular propagation model associated with the IEMCAP is based on aircraft and spacecraft/missile systems. This model calculates the propagation loss associated with an electromagnetic coupling path when both source and receptor are located on the same craft. Associated with this model is a vehicular model for determining antenna separation distances. The vehicular model determines the combination of straight lines, concial spirals and/or cylindrical spirals that gives the shortest distance between two antennas over a spacecraft or aircraft surface. The distances computed are used in the fuselage (cylindrical) shading and/or wing diffraction computations to determine the total shading factor portion of the propagation model.

A typical system (aircraft, spacecraft or ground system) may contain thousands of ports. If every emitter port had to be analysed in conjunction with every receptor port, the run time, core memory size and file storage requirements would be prohibitive for most computer systems. A compromise set of conditions was established and the capacity of IEMCAP with regard to run size is given in Table 1. For systems which exceed these limits, multiple computer runs would be required.

Table 1

MAXIMUM RUN SIZE	
EQUIPMENTS	40
PORTS PER EQUIPMENT	15
TOTAL PORTS (40 X 15)	600
APERTURES	10
ANTENNA TYPES	50
FILTER TYPES	20
WIRE BUNDLES	140
TOTAL NUMBER OF WIRES	280
BUNDLE POINTS PER WIRE	11
BUNDLE SEGMENTS	140

The defined frequency range of analysis for the IEMCAP is 30 Hz to 18 GHz. These limits are based on the prestored models associated with the program such as the MIL-STDS.

(3) Applicability of IEMCAP to Systems Analysis

The objective of this effort is to establish the IEMCAP as an integral part of the overall system test procedures. The use of IEMCAP will provide the capability of both generating system specification limits and maintaining the integrity of the system specification with system modification. In addition, it provides a needed interface between the EMC engineer and the system design engineer.

IEMCAP is a computerized analysis process which can be used to establish and maintain cost-effective interference control throughout the life cycle of systems composed of communications and electronics equipment. Fundamental to the major options of IEMCAP are the following built-in capabilities:

- Provides system data base
- Complete description of system emissions, susceptibilities, EM coupling, and EMI
- System specifications
- Defines measurement requirements

One of the most significant capabilities of IEMCAP is the generation of a system data base which can be continually maintained and updated to follow system design changes/modifications. The data base created by the IEMCAP will result in rapid and economical analysis of modifications.

IEMCAP provides a complete description of system emissions, susceptibilities, EM coupling paths and the electromagnetic interference conditions. The emissions and susceptibilities, both required and non-required, are represented in IEMCAP by spectra (frequency versus amplitude characterizations). For each emitter port, a two-component (broadband and narrowband) spectrum represents the power levels produced over the frequency range. The broadband component consists of noiselike or largely unintentional emissions, that are fairly constant over wide frequency ranges whereas the narrowband component is usually well defined within a limited frequency range. The broadband components are in units of power spectral density. The narrowband components are in units of power.

For each receptor, a spectrum represents its susceptibility threshold versus frequency characteristic. This susceptibility standard threshold is the level of minimum received signal which produces a standard response at a given frequency.

A frequency range is defined as the required range for each intentional port. Signals within this range are those required for operation, and therefore not adjustable for EMC purposes. Outside this range specified limits may be established for the maximum emission and minimum susceptibility levels. The spectrum within the required range can be defined by a mathematical model. This is done by using the theoretical equations of the frequency domain representation of the signal, or may be input as a user-defined spectrum.

The specification generation process adjusts these assumed spectrum levels to achieve compatibility if interference is indicated. By readjusting the spectra of emitters and receptors the maximum non-required emission and minimum susceptibility levels are obtained for a compatible system. The IEMCAP system specifications also establishes the measurement requirements.

b. Broadband Measurements of Emissions

Tuneable receivers are presently required for MIL-STD-461 emission measurements. The time required to make the measurements, and thus the expense, could be reduced if the measurements could be made with broadband, non-tuneable equipment.

Opening up the measurement bandwidth would, at first glance appear to introduce thermal noise which would rapidly exceed the present narrowband emission specification limits. This could be accepted on a system basis by raising the specification limits where the probability of susceptibility is known to be low and the signal level that produces a susceptible response is known to be high. As it turns out, thermal noise can be reduced by post-detection filtering and the problem is obtaining enough dynamic range to accommodate broadband impulse signals.

Each of the components which make up a hypothetical broadband measurement system will be investigated in the following subsections for factors which affect their practical realization. Performance will then be analyzed for measurements on three signal types: CW, random noise and impulses. In this report CW and impulse signals are analyzed with respect to random noise. In later work in this contract random noise as a signal (such as spread spectrum or noncoherent signals, for example) will be considered. The impact on the applicable MIL-STD-461 specification limits will then be examined.

(1) Hypothetical Broadband Measurement System

A broadband measurement system is hypothesized in Figure 2. The system is essentially a crystal-video receiver with a peak detector on the output. The entire range from 14 kHz to 10 GHz is covered by three antennas in five bands. The broadband system shown can be assembled for less than the cost of a single EMI receiver covering only a portion of the range.

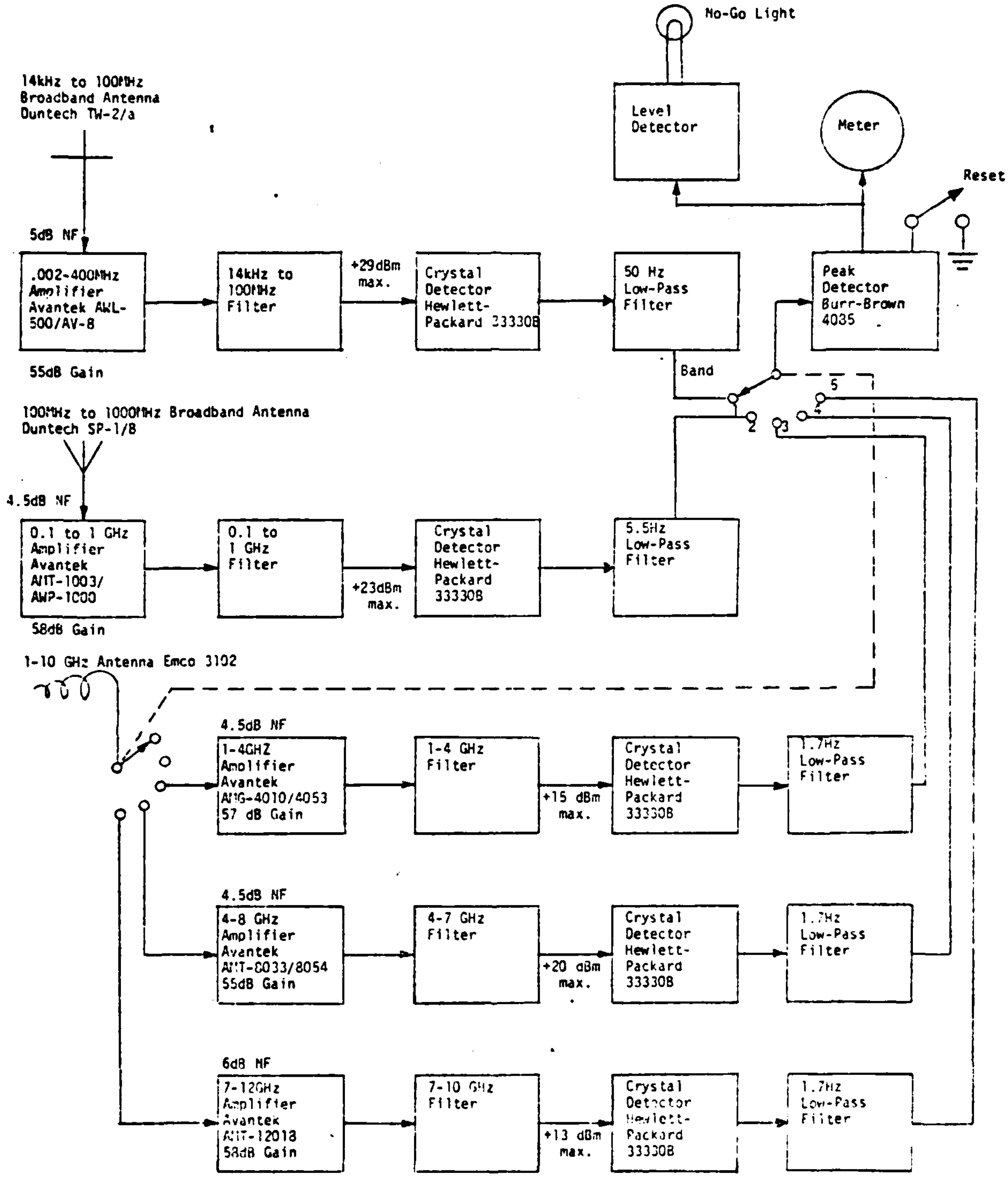

Figure 2. Broadband Measurement System Block Diagram.

Up to 1 GHz, the system band edges are determined primarily by the available broadband antennas. From 1 to 10 GHz, the band edges are determined by the availability of suitable wideband amplifiers. Filters are used between the amplifiers and the detectors to determine the band edges so that out-of-band noise does not reach the detectors. Separate detectors are used so the need for RF switching can be reduced.

Each band is covered by a wideband antenna, amplifier, crystal detector and low-pass filter, followed by a peak detector and indicator (meter) with a go/no-go presentation which is common to all bands. Simultaneous coverage of all bands would be possible if a multiplexer was used with the microwave antenna, or three separate microwave antennas were used. The system is applicable to conducted emission measurements by replacing the antennas with suitable wideband probes. However, the initial concern is for radiated measurements.

(a) Broadband Antennas

The entire range from 14 kHz (or down to 20 Hz, if desired) to 10 GHz could be covered by two antennas: the SP-1/B made by Duntech Industries covering 20 Hz to 1 GHz in two bands, and the Emco 3102 covering 1 to 10 GHz in a single band. However, the Duntech TW-2/A has a flatter antenna factor and higher saturation point over the 20 Hz to 100 MHz low band than the SP-1/B and has been selected for the hypothetical system.

Both the TW-2/A and the SP-1/B are "active" antennas in that they incorporate FET amplifiers in their bases to accomplish impedance transformation and/or preamplification. Unlike passive antennas, active antennas contribute amplifier noise to the system and must be used with care in noisy environments to avoid saturation by strong signals. Only an active antenna can provide the many decades of flat frequency response needed by the broadband system at the lower frequencies.

The broadband noise thresholds provided by the antennas and preamplifiers in the hypothetical system are compared with the MIL-STD-461 limits in Figure 3. The threshold for the TW-2/A, when used with a conventional 20 kHz bandwidth receiver is also shown for comparison. (At threshold RMS signal voltage = RMS noise voltage.)

While it would appear from the curves that broadband antenna/amplifier input noise would prevent measurement to existing narrowband specification limits with a broadband system, it will be seen later that post-detection filtering can allow existing narrowband limits to be met.

(b) 14 kHz to 100 MHz Antennas

The Duntech Industries Model TW/2-A antenna selected for the 14 kHz to 100 MHz band is a relatively new device covering 20 Hz to 100 MHz in one band with published data indicating a constant antenna factor of 6 dB within 0 to +2 dB from 100 Hz to 100 MHz. Physically the antenna is a 64 inch rod standing over a ground plane of 18 inch radials. An active FET base amplifier converts the high impedance voltage output of the rod to 50 ohms for field strengths up to 20 volts/meter (V/m).

The published antenna factor and the approximate noise output (measured with a 5 dB noise figure system on an equivalent FET device because detailed noise data are not available from Duntech) are plotted in Figure 4. (The published data may be in error in not showing any quarter-wave resonance effects around 60 MHz. These effects can generally only be avoided in active antennas by using shorter whips which result in larger antenna factors). The staircase approximation on the noise plot was used to integrate the total noise power over the 10 kHz to 100 MHz bandwidth as shown in Table 2. This was found to be 1.8×10^{-11} watt, or 29.5 dBμV in 50 ohms, which corresponds to an overall noise figure of 16.4 dB including the 5 dB noise figure preamplifier. In spite of the large 1/f characteristic, most of the noise is contributed by the last frequency decade between 10 and 100 MHz.

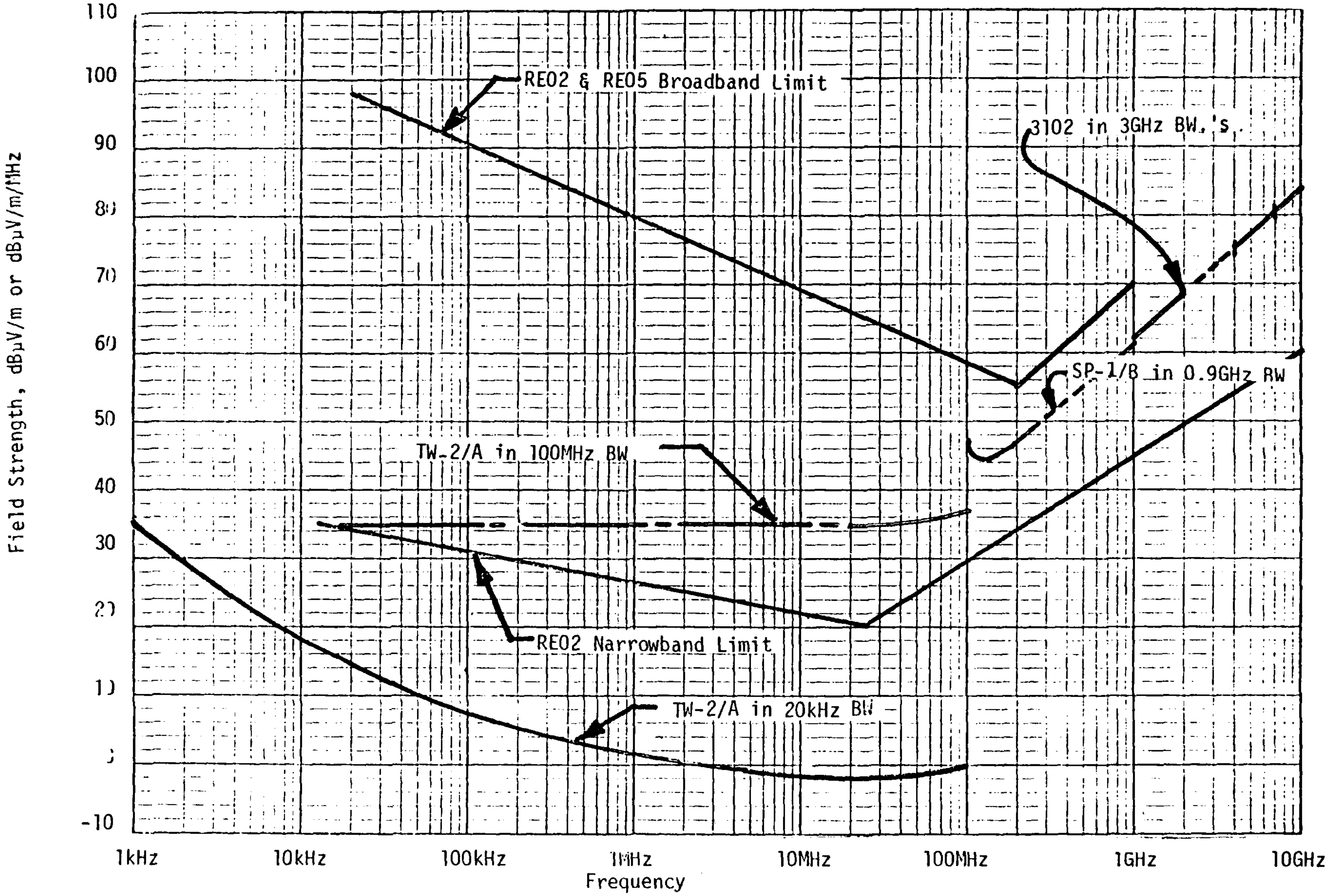

Figure 3. Broadband Pre-Detection Noise-Limited System Sensitivity.

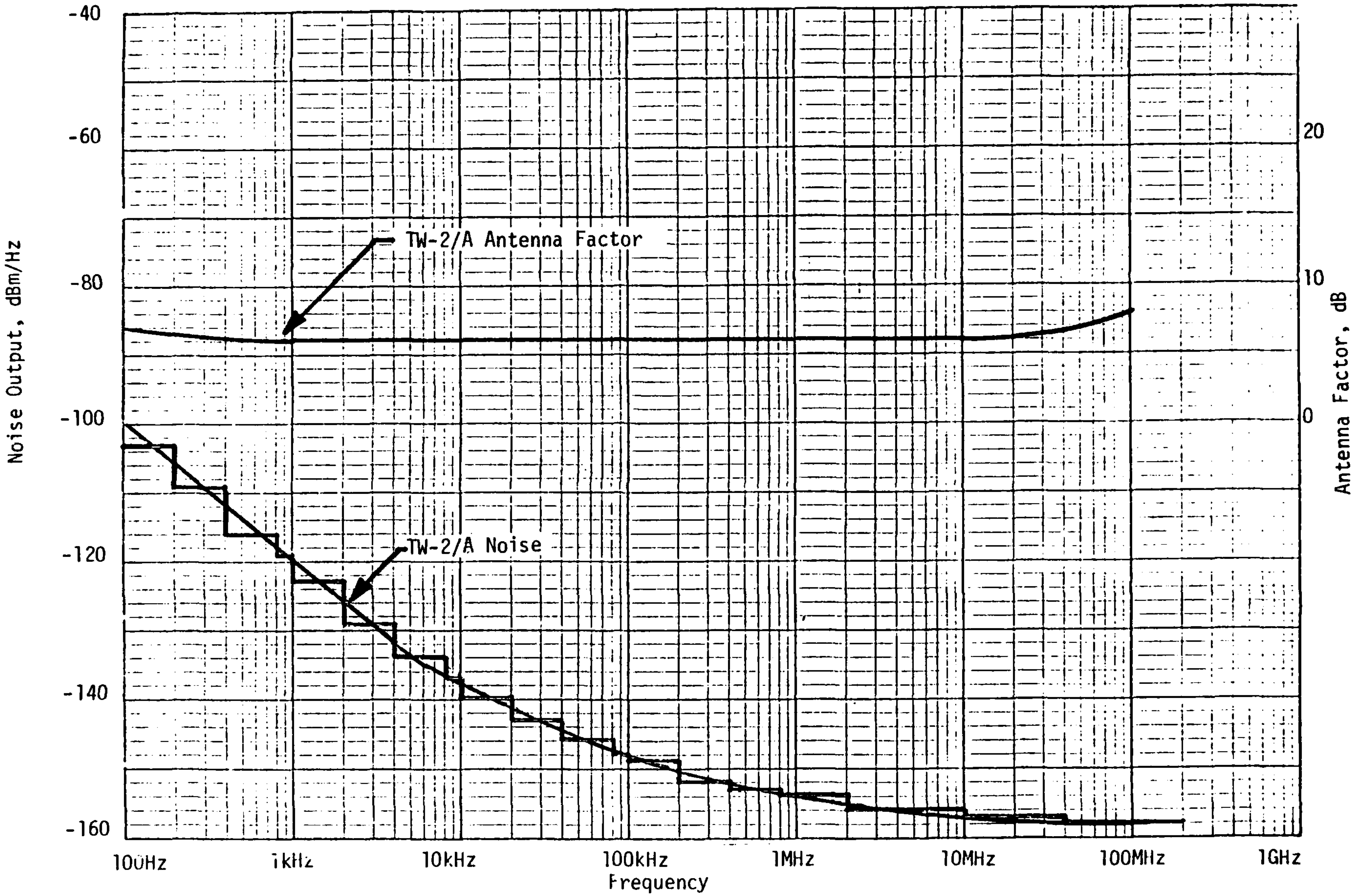

Figure 4. TW-2/A Antenna Characteristics.

Table 2. TW-2/A Noise Integration.

Frequency Range	Noise Level	Bandwidth	Noise Power
10-20 kHz	-140 dBmV/Hz	10 kHz	1.000×10^{-13}W
20-40	-143	20	1.002×10^{-13}
40-80	-146	40	1.005×10^{-13}
80-100	-148	20	3.170×10^{-14}
100-200	-149	100	1.259×10^{-13}
200-400	-152	200	1.262×10^{-13}
400-800	-153	400	2.005×10^{-13}
800-1 MHz	-154	200	7.962×10^{-14}
1-2	-154	1 MHz	3.981×10^{-13}
2-4	-156	2	5.024×10^{-13}
4-8	-156	4	1.005×10^{-13}
8-10	-156	2	5.024×10^{-13}
10-20	-157	10	1.995×10^{-12}
20-40	-157	20	3.991×10^{-12}
40-80	-158	40	6.340×10^{-12}
80-100	-158	20	3.170×10^{-12}
			1.786×10^{-11}W
			= -107.5 dBW
			= - 77.5 dBm
			= 29.5 dBμV*

* In a 50-ohm system.

(c) <u>0.1 to 1.0 GHz Antenna</u>

From 0.1 to 1 GHz, the Duntech SP-1/B has been selected because of its relatively small size and flat gain. The antenna is bi-conical, 22 inches high by 38 inches in diameter. The base contains an active preamplifier with 6 dB noise figure, 10.5 dB gain and +10 dBm output capability. Overload (saturation) occurs at 2 V/m field strength.

The data for the SP-1/B are abstracted from published curves in Table 3. The antenna factors shown include the gain of the preamplifiers.

Table 3. Duntech SP-1/B Antenna Characteristics

Frequency	Antenna Factor	Threshold Field Strength
100 MHz	8 dB/m	47.1 dBμV/m
150	5	44.1
200	8	47.1
400	14	53.1
800	20	59.1
1000	22	61.1

The threshold field strength, FS, was obtained as

$$\begin{aligned} FS &= 20 \log_{10}(KTR)^{0.5} + 10 \log_{10}(B) + F + G + F_A \\ &= -66.9 + 89.5 + 6 + 10.5 + F_A \\ &= 39.1 + F_A \text{ dB}\mu\text{V/m} \qquad (1) \end{aligned}$$

where $(KTR)^{0.5}$ is the thermal noise voltage from a resistor at 24°C in $\mu V/\sqrt{Hz}$, B is bandwidth in Hz, F is noise figure in dB, G is preamplifier gain in dB and F_A is the antenna factor including the preamplifier in dB/m. The threshold field strength is plotted in Figure 3, assuming a 50-ohm system.

(d) 1 to 10 GHz Antenna

There are quite a few antennas available which cover the 1 to 10 GHz frequency range in one band. One which has been widely used for EMI measurements and on which data are readily available is the Emco 3102 conical log spiral. The antenna is a cone approximately 3 feet long and a foot in diamter at the base. The antenna has circular polarization.

The published antenna factors are listed in Table 4. The threshold field strengths were obtained using Equation (1) with G = 0 and B = 3 GHz. The values are plotted in Figure 3.

Table 4. Emco 3102 Antenna Characteristics

Frequency	Antenna Factor	Threshold Field Strength
1 GHz	26.0 dB/m	61.6 dBμV/m in 3 GHz BW
2	32.6	68.2
4	39.0	74.6
7	44.1	79.7
10	47.2	82.8

(2) Wideband Amplifiers

The wideband amplifiers for use in the hypothetical Broadband Measurement System were selected on the basis of frequency coverage, input noise figure and power output. Gain is also important but gain need only be sufficient to drive the crystal detectors into a suitable operating region with amplifier noise so that the amplifiers determine the system noise figure. The amplifier characteristics are listed in Table 5.

Table 5. Wideband Amplifier Characteristics.

Band	Manufacturer	Model	± 1 dB Frequency Response	Noise Figure	Gain	Power Output
1	Avantek	AWL-500	.001 - 500 MHz	5.0 dB	25 dB	+5 dBm
1	Avantek	AV-8	.002 - 400	10.0	30	+29
2	Avantek	AMT-1003	100 - 1000	4.5	28	+6
2	Avantek	AWP-1000	10 - 1000	7.5	30	+23
3	Avantek	AMG-4010	1000 - 4000	4.5	32	+12
3	Avantek	AMG-4053	1000 - 4000	4.8	25	+15
4	Avantek	AMT-8033	4000 - 8000	4.5	27	+13
4	Avantek	AMT-8054	4000 - 8000	5.5	28	+20
5	Avantek	AMT-12018	7000 - 12000*	6.0	58	+13

* ± 2 dB

The gains used in the block diagram of Figure 2 must be considered tentative because they are based on a nominal crystal video detector sensitivity of -50 dBm which would not be realistic if the detectors are heavily resistively loaded to obtain wide video bandwidths.

The amplifiers listed in Table 5 are all made by Avantek. Similar amplifiers are made by Watkins-Johnson and others, but those listed are representative of the state-of-the-art. It would be desirable if somewhat greater power output were available for driving the crystal detectors to their full + 23 dBm rating above 1 GHz.

(3) Crystal Detectors

Two types of crystal detectors are generally available; the older types using point-contact diodes and the newer types using low-barrier Schottky diodes. The primary difference is sensitivity, the Schottky diodes typically producing 5 mill-volts output per microwatt input compared with 0.4 for good point-contact diodes. The Schottky diodes may also prove somewhat more stable and reliable because the diffused junction construction eliminates the mechanical "cat-whisker" contact. Detector stability will be an important consideration if the Broadband Measurement System is to maintain calibration.

Detector sensitivity is important because it affects dynamic range. The system needs all the dynamic range it can get to handle broadband interference in the extremely wide bandwidths being considered here. More about dynamic range later.

The most important detector characteristic is video bandwidth. Broadband measurements will be acceptable only if all signals within the bandwidth are handled in a controlled manner so that specification limits can be applied independent of frequency and signal characteristics. There are two choices of detector characteristics which can accomplish this ideal: peak or average.

The peak detector has essentially zero video bandwidth, the output being a DC level proportional to the peak of any input signal which comes along, whether it occurs repeatedly as do the peaks of a sine wave, or only occasionally as do impulses. A true peak detector is difficult to realize for an impulse with a bandwidth greater than a few megahertz because there is insufficient time to fully charge a storage capacitor. Narrowband signals do not have this problem because the storage capacitor charge can be built up over several cycles. A compromise position might be taken where a charging time constant is specified (infinite manual discharge is assumed) to provide a relationship between amplitude and frequency of occurrence, but this is likely to be messy specification-wise.

The average detector has a video bandwidth (post-detection bandwidth) equal to the RF bandwidth (pre-detection bandwidth). The output of the detector before the video low-pass filter is an accurate rectified replica of the input, the average DC value of which is passed by the filter to the output along with video components within the filter passband. The average detector has an important advantage over the peak detector in that the ratio of the broadband response, as represented by an impulse, to the narrowband response, as represented by CW, can be controlled by controlling the ratio of the pre-detection to the post-detection bandwidth. (The required bandwidth ratios will be derived in a later Section.) Realization of the average detector is fairly simple up to video bandwidths in the gigahertz range by using low capacitance crystal holders and low values of video load resistance. Typical values are 3 pF for available video output capacitance, C_o, and 50 ohms for video load resistance, R_o, giving a detector time constant, t_o, of:

$$\begin{aligned} t_o &= 2.2\ R_oC_o \\ &= 2.2\ (50)(3 \times 10^{-12}) \\ &= 3.3 \times 10^{-10} \text{ second} \end{aligned} \tag{2}$$

Taking the reciprocal gives a video bandwidth on the order of 3 GHz.

Two disadvantages of the low video load resistance required by the average detector are that it reduces detector sensitivity over that of a peak detector and that the resistance value is considerably below the several hundred ohms required for optimum square-law response (the exact value depends on the specific crystal). Both disadvantages are secondary to the realizability and to the controlled narrowband/broadband response capability criteria. The reduction in sensitivity can be offset by increasing RF amplifier gain (with some loss of dynamic range). The response law is not critical in a system that will operate with a fixed threshold.

Full-wave detectors should be used to make the response insensitive to impulse polarity and improve sensitivity.

(4) Peak Detector and Output Indicator

It is intended that the hypothetical Broadband Measurement System will produce a go/no-go indication of EMI emissions. Assuming that an average detector is used for conversion of RF to video, the video will be processed by a peak-hold circuit and the long-term peak value displayed on a meter calibrated in dB relative to the specification limit. A level detector will also illuminate an indicator lamp when the specification limit is exceeded. The indicators will be manually reset by a pushbutton.

The long-term peak-hold circuit will require an easily attained response time of 20 milliseconds with good accuracy. This can be accomplished with analog circuitry or by digitizing at a 100 Hz, or greater, sample rate. The digital approach has the advantages of being able to accomplish an indefinite peak-hold function without drift problems and, with a microprocessor, of easy adaptability to various crystal detector response characteristics for production of a decibel display.

(5) <u>Broadband Measurement Sensitivity</u>

Given a crystal-video receiver consisting of an RF amplifier with sufficient gain that the amplifier noise figure, F, determines the system noise figure, a pre-detection filter of bandwidth B_I, a square-law crystal detector, and a post-detection filter of bandwidth B_O, the input signal level required for a 0 dB signal-to-noise ratio (S/N) at the output will now be determined.

(a) <u>CW Sensitivity</u>

A square-law detector with a band-limited Gaussian noise input of power N watts/Hz is assumed to have as its output a triangular noise distribution caused by noise components interacting with noise components ((N)x(N) noise), as shown in Figure 5. The area of the triangle and the area of the rectangle are both proportional to the noise input power, P_{NI}. Since the bandwidth for both is the pre-detection bandwidth, B_I, the height of the triangle at zero frequency is twice that of the rectangle. The area, P_{NO}, of that portion of the triangle representing the noise power which passes through the post-detection bandwidth, B_O, is:

$$P_{NO} = 2\ NB_O - (XB_O/2)$$

$$= \frac{2\ NB_O B_I - NB_O^{\ 2}}{B_I} \tag{3}$$

The detection bandwidth ratio, b, which determines the portion of the noise input power, P_{NI} which appears in the output as P_{NO} is $b = P_{NO}/P_{NI} = P_{NO}/NB_I$, from which:

$$b = \frac{2\ B_O B_I - B_O^{\ 2}}{B_I^{\ 2}} \tag{4}$$

Because of the square-law detector characteristics, the signal output power, P_{SO}, and the noise output power, P_{NO},

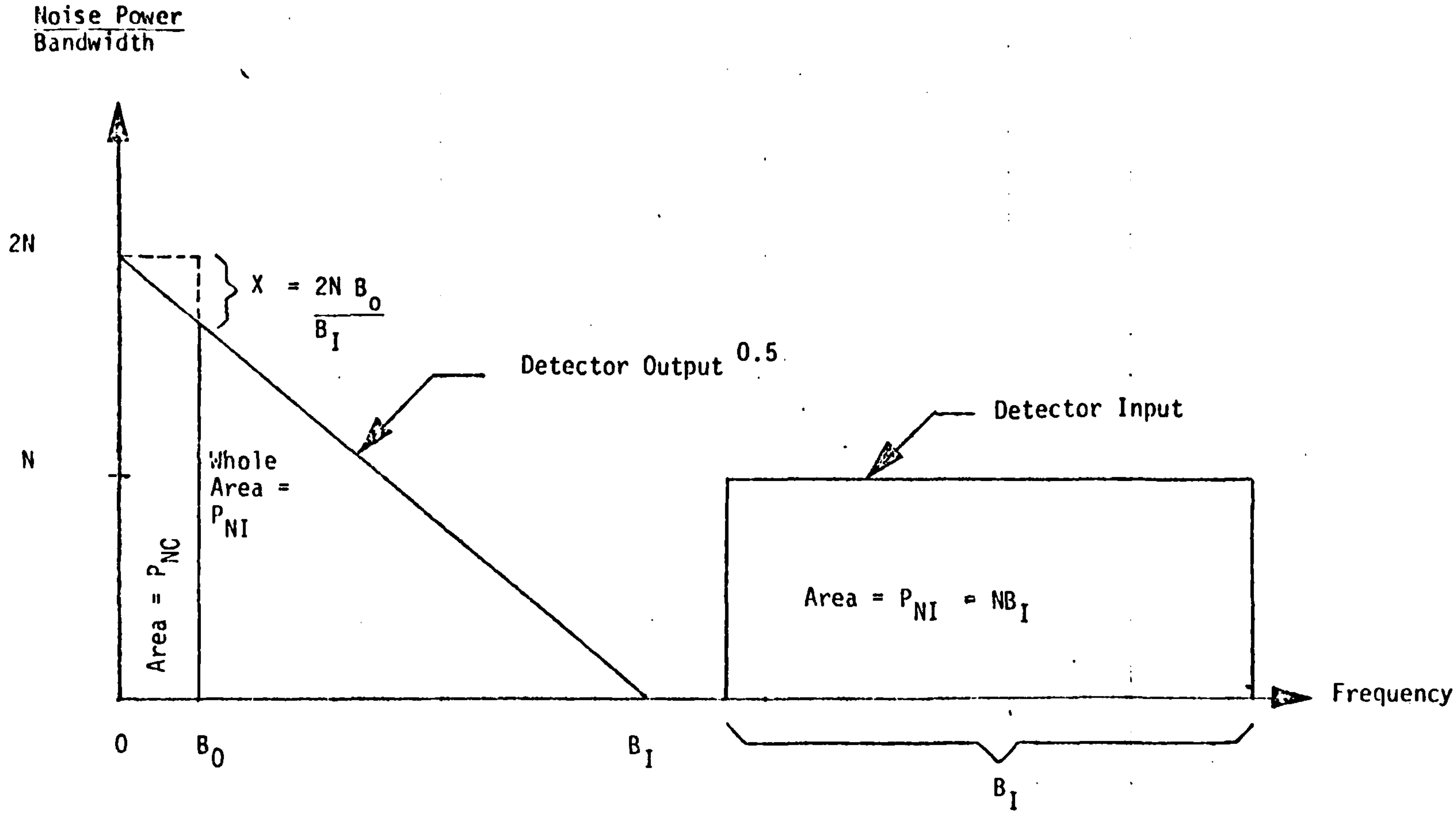

Figure 5. Detector Input and Output Noise Distributions.

are the squares of the corresponding inputs.

$$P_{SO} = (CP_{SI})^2 \tag{5}$$

and

$$P_{NO} = b(CNB_I)^2 \tag{6}$$

where C is a detector sensitivity constant (V/W). At threshold, $P_{SO} = P_{NO}$ and:

$$(CP_{SI})^2 = b(CNB_I)^2$$

$$= \frac{(2\ B_O B_I - B_O^2)(CNB_I)^2}{B_I^2}$$

$$P_{SI} = N(2\ B_O B_I - B_O^2)^{0.5} \tag{7}$$

Expressed in decibels:

$$P_{SI} = 10 \log_{10} N + 5 \log_{10}(2\ B_O B_I - B_O^2)$$

Using a wideband RF preamplifier with noise figure, F, in dB, and sufficient gain, the threshold input signal power is:

$$P_{SI} = 10 \log_{10} kT + F + 5 \log_{10}(2\ B_O B_I - B_O^2)$$

$$= -203.9 + F + 5 \log_{10}(2\ B_O B_I - B_O)\ \text{dBW} \tag{8}$$

where -203.9 is thermal noise in dBW/Hz at 24°C and bandwidths are in hertz. Where the RMS signal input voltage sensitivity, V_{SI}, is required in a 50-ohm system and the bandwidths are in megahertz:

$$V_{SI} = -6.9 + F + 5 \log_{10}(2\ B_O B_I - B_O^2)\ \text{db}\mu\text{V} \tag{9}$$

(The above equation is for RMS S/N=0 dB at the video output. Add 6.5 dB to V_{SI} for a peak S/N=0 dB output criteria. Input values are assumed to be RMS).

The preamplifier gain, G, required for the system noise figure to essentially equal that of the preamplifier is given by:

$$G \geq |P_{SI} - P_D| + 3 \text{ dB} \tag{10}$$

where P_D is the threshold sensitivity of the detector alone (typically -50 dBm).

The above sensitivity analysis does not take into account the additional input noise transferred to the output in the presence of the signal because of signal components interacting with noise components ((S)x(N) noise). The noise output from a detector increases when a signal appears, leading to what has been termed the "small-signal suppression effect." For a detector operating at full bandwidth, (i.e. $B_O=B_I$), a 5 dB RMS input S/N is typically required for a 0 dB RMS output S/N. However, when B_O is much smaller than B_I, which is the case of interest here, the concentration of (N)x(N) noise near zero frequency, as represented by the triangular noise distribution in the detector output, tends to swamp out the effect of (S)x(N) noise so that it will be neglected for the present.

(b) Impulse Sensitivity

An impulse (a pulse sufficiently short that the energy is constant across the input bandwidth, B_I) is assumed to react in a detector much the same as noise in that the detector output pulse power distribution, P_{IO}, is triangular because impulse components interact with impulse components ((I)x(I) components) to concentrate energy near zero frequency. Unlike noise, the impulse components are correlated so that peak voltage as well as power is directly proportional to bandwidth. This leads to the calibration of impulse generators in units of V/Hz, or dbμV/MHz.

A suitable threshold criteria for evalutaing the sensitivity of a crystal video receiver to impulses is that the peak voltage of the impulse output, V_{IO}, equal the peak voltage of the noise output, V_{NO}. Experimental data obtained by observing noise with a known RMS value on an oscilloscope indicate that

$$\begin{aligned} V_{NO} &= 3(R_O P_{NO})^{0.5} \\ &= 3(\text{RMS value}) \end{aligned} \tag{11}$$

when most of the frequently occuring peaks are included. (R_O is the video load resistance.)

Narrowband Gaussian noise has a Rayleigh envelope distribution for which the probability, P, that a given level, R, is exceeded is given by:[1]

$$P = e^{\frac{-R^2}{2}} \tag{12}$$

The RMS value of the distribution corresponds to $R = \sqrt{2}$. Levels 3 times the RMS value will be exceeded with a probability of

$$\begin{aligned} P &= e^{-(3\sqrt{2})^2/2} \\ &= 0.0001 \end{aligned}$$

Another way of looking at it is that noise peak voltage will be less than three times the RMS voltage noise 99.99 percent of the time. The probability that the threshold will be exceeded must be small if a peak-hold circuit is to be used at the output to provide a go/no-go indication.

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1. Di Franco and Rubin: "Radar Detection" Prentice-Hall, 1968, p 304.

For a square-law detector, the peak impulse voltage output, V_{IO}, is related to the impulse input, I, in RMS volts per hertz, by:

$$V_{IO} = Cb(\sqrt{2}\ I\ B_I)^2/R_I \tag{13}$$

and the Rayleigh noise output peak voltage, V_{NO}, is related to the Gaussian input noise, N, in watts per hertz by:

$$V_{NO} = 9/\sqrt{6}\ C\ N\ B_I \tag{14}$$

The variables are as previously defined in the derivation of CW sensitivity (see Subsection (a)). At threshold:

$$V_{IO} = V_{NO}$$

and

$$Cb(\sqrt{2}\ IB_I)^2/R_I = 9/\sqrt{6}\ CNB_I$$

$$I = \left[\frac{4.5\ NR_I}{\sqrt{6}\ B_I}\right]^{0.5}$$

$$= \left[\frac{4.5\ NR_I}{(2\ B_O B_I - B_O^2)^{0.5}}\right]^{0.5} \tag{15}$$

Expressed in decibels:

$$I = 6.5 + 10\ \log_{10} N + 10\ \log_{10} R_I$$

$$-5\ \log_{10}\ (2\ B_O B_I - B_O^2)$$

$$= -180.4 + F - 5\ \log_{10}(2\ B_O B_I - B_O^2)\ \text{dBV/Hz} \tag{16}$$

for a 50-ohm system where B_O and B_I are in hertz, or

$$I = -0.4 + F - 5\ \log_{10}(2\ B_O B_I - B_O^2)\ \text{dB}\mu\text{V/MHz} \tag{17}$$

where B_O and B_I are in megahertz.

(c) Impulse/CW Response Ratio

It is desirable that any broadband measurement system allow a higher limit for broadband emissions in dBμV/MHz than for narrowband emissions in dBμV. Broadband measurement systems are inherently more sensitive to broadband interference than narrowband systems and, when the system bandwidth exceeds 1 MHz, can be numerically more sensitive to broadband interference than to narrowband interference. Thus, if the broadband measurement system being considered here (input bandwidths considerably wider than 1 MHz) is to make measurements without having to be recalibrated for each type of interference, the broadband response must be reduced by a known amount relative to the narrowband response. This can be done by controlling the pre-detection to post-detection bandwidth ratio.

Taking CW as the worst-case (narrowest bandwidth) narrowband interference and an impulse as the worst-case broadband interference, the peak output voltages from the detector are:

$$V_{SO} = 2\ CP_{SI} = C(\sqrt{2}\ V_{SI})^2/R_I \tag{18}$$

and

$$V_{IO} = Cb(\sqrt{2}\ IB_I)^2/R_I \tag{19}$$

where V_{SI} is a CW signal in RMS microvolts and I is an impulse signal in RMS microvolts/MHZ. For equal outputs ($V_{SO} = V_{IO}$), the required inputs are:

$$C(\sqrt{2}V_{SI})^2/R_I = bC(\sqrt{2}\ I\ B_I)^2/R_I$$

$$V_{SI} = \sqrt{b}I\ B_I \tag{20}$$

and the impulse/CW response ratio, r, is:

$$r = \frac{I}{V_{SI}}$$

$$= \frac{1}{\sqrt{6}B_I}$$

$$= \frac{1}{(2B_O B_I - B_O^2)^{0.5}} \qquad (21)$$

where B_O and B_I are in MHz if I is in μV/MHz and V_{SI} is in μV. If $B_O \ll B_I$,

$$B_O \approx 1/(2B_I r^2) \qquad (22)$$

It appears that once B_I and B_O have been selected, all other types of RFI, such as uncorrelated noise and complex mixtures, will have r values falling somewhere between CW and impulses.

(6) Broadband Measurement System Capability

Traditionally MIL-STD-461 has allowed a numerically higher limit on radiated broadband emissions than on radiated narrowband emissions. This is partially due to the fact that the standard narrowband measurement equipment has bandwidths considerably less than 1 MHz, making it inherently less sensitive in broadband units of dbμV/MHz than in narroband units of dBμV, and partially due to the fact that broadband emissions generally have less interference effect (lower energy density) than narrowband emissions of equivalent peak value. Section 3b(5)(c) shows that the broadband-to-narrowband response ratio (assumed here to be identical to the impulse/CW response ratio as worst-case) can be controlled in a Broadband Measurement System by controlling the ratio of the pre-detection to the post-detection bandwidths. Thus, it is feasible to write a unified specification in which the broadband and narrowband limits differ in such a way that the measurements can be accomplished with a simple broadband measurement system without regard for the emission characteristics.

(a) Choice of r

For the hypothetical Broadband Measurement System first cut, 20 dB was chosen for the broadband-to-narrowband response ratio, r. This value was selected because it is the lowest ratio between the RE02 curves (occuring at 200 MHz) and results in a similarity between the old and new curves. Almost any other positive (or even negative with B_I > 1 MHz) ratio could have been chosen, but lower ratios would be more desirable than higher because they lead to smaller dynamic range requirements.

Using Equation (22), the post-detection bandwidth, B_O, required for a 20 dB broadband-to-narrowband voltage response ratio is:

$$B_O \approx 1/(2\ B_I r^2)$$

For Band 1,

$$B_O \approx 1/2(100)(10)^2 = 50 \text{ Hz}$$

For Band 2,

$$B_O \approx 1/2(900)(10)^2 = 5.5 \text{ Hz}$$

For Bands 3, 4, and 5,

$$B_O \approx 1/2(3000)(10)^2 = 1.7 \text{ Hz}$$

These values were used for the video low-pass filters in the Hypothetical Broadband Measurement System shown in Figure 2.

The above post-detection bandwidths are too narrow to pass most intentional modulations. They are just wide enough to pass the necessary measurement information, which is primarily DC for narrowband signals and primarily AC for low-duty-cycle broadband signals.

(b) System Sensitivity

Substituting B_0 into Equations (9) and (17) results in the sensitivities shown in Table 6 for the system without antennas using detectors with nominal tangential sensitivities of -55 dBm. The threshold field strength sensitivities can then be calculated as shown in Table 7. The corrected values shown for amplifier gain and conducted sensitivity in Table 7 result because the Band 1 and 2 antennas incorporate amplifiers whose gain has been included in the antenna factors and therefore reflect in the calculations as degraded antenna noise figures.

The threshold field strengths for the hypothetical Broadband Measurement System are plotted along with the present RE02 limits in Figure 6. Note that the broadband system can meet the RE02 limits for narrowband emissions. If the post-detection bandwidths are changed, narrowband sensitivity decreases at the rate of 5 dB/decade of post-detection bandwidth increase, and broadband sensitivity increases at the rate of 5 dB/decade increase, resulting in a change in ratio of 10 dB/decade.

(c) Hypothetical Broadband Measurement Specification First Cut

A set of hypothetical new limit curves is shown with dashed lines on Figure 6. With the exception of a dynamic range problem to be evaluated in the next Section, and a narrow region between 100 and 150 MHz, the new limits could be measured by the broadband system to within ±1 dB over the entire range from 14 kHz to 10 GHz for any type of signal from pure CW to impulse. The problem between 100 and 150 MHz is caused by a drop in antenna gain in this region. With the problem range included, accuracy would be ±3 dB or, more accurately, +6 to -0 dB.

The new limit curves are flat from 14 kHz to 100 MHz, reflecting the flat active antenna gain characteristic. Above 100 MHz, the limit curves rise at the rate of 20 dB/decade re-

Table 6. Sensitivity Without Antennas

Band	Frequency Range	Amplifier Noise Figure	Pre-Detection Pandwidth	Post-Detection Bandwidth	Pre-Detection Gain Required	*Conducted CW Sensitivity
1	14 kHz-100 MHz	5.0 dB	100 MHz	50 Hz	60.4 dB	-5.4 dBμV
2	100-1000 MHz	4.5	900	5.5	62.9	-5.9
3	1-4 GHz	4.5	3 GHz	1.7	60.9	-5.9
4	4-7 GHz	4.5	3	1.7	60.9	-5.9
5	7-10 GHz	6.0	3	1.7	58.9	-4.4

*CW input for peak signal = peak noise at detector output.

Table 7. Sensitivity With Antennas

Band	Frequency	Amplifier Noise Figure	Antenna Noise Figure	Corrected Gain Required*	Corrected CW Sensitivity	Antenna Factor	Threshold Field Strength
1	10 kHz	5.0 dB	16.4 dB	48.4 dB	6.0 dBμV	6 dB/m	12.0 dBμV/m
	10 MHz					6	12.0
	100					8	14.0
2	100 MHz	4.5	16.5	48.9	6.1	8	14.1
	150					5	11.1
	200					8	14.1
	400					14	20.1
	800					20	26.1
	1000					22	28.1
3	1 GHz	4.5	0	60.9	-5.9	26.0	20.1
	4					39.0	33.1
4	4 GHz	4.5	0	60.9	-5.9	39.0	33.1
	7					44.1	38.2
5	7 GHz	6.0	0	58.9	-4.4	44.1	39.7
	10					47.2	42.8

* Gains reduced in Bands 1 and 2 because of antenna noise.

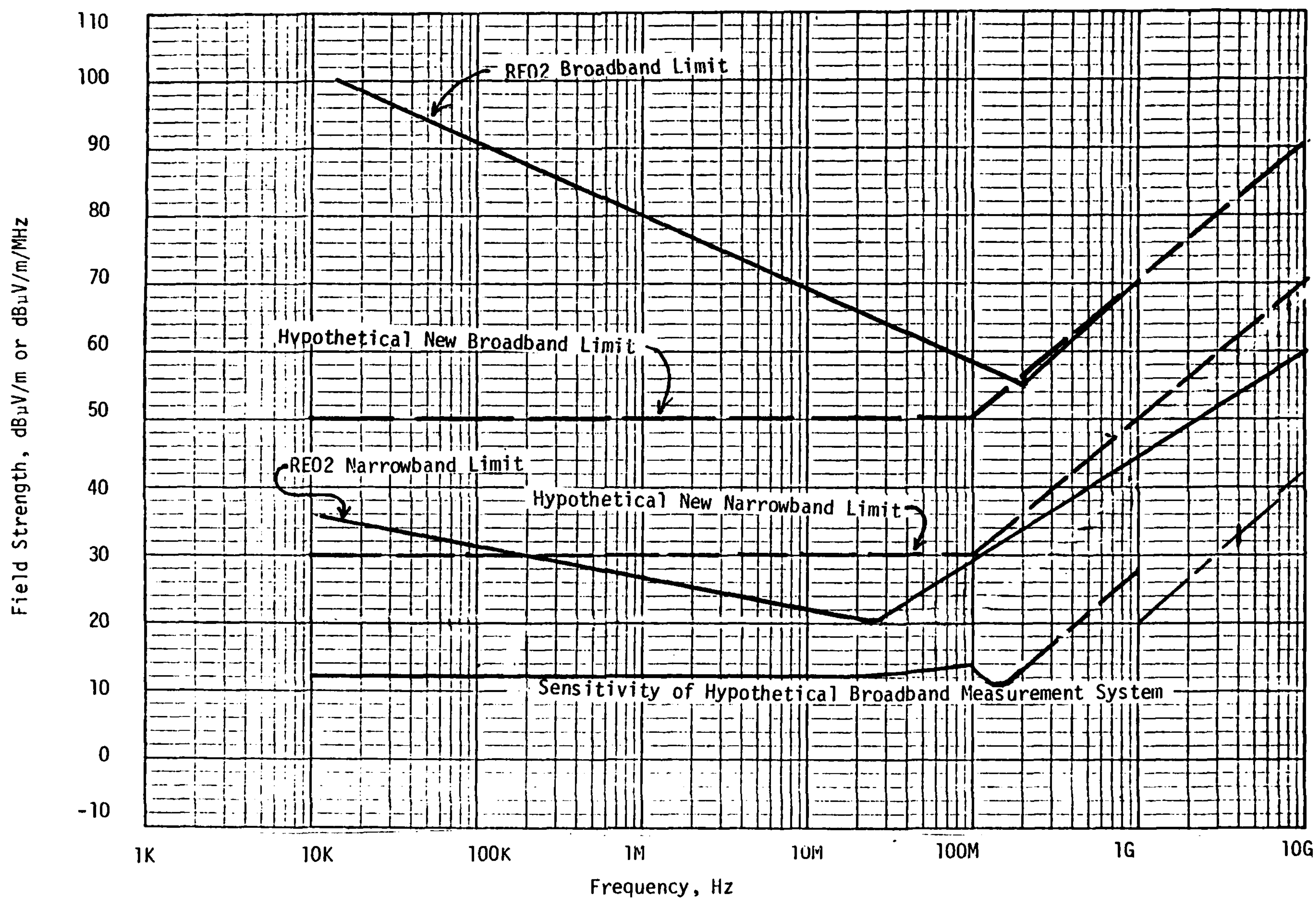

Figure 6. Hypothetical Braodband Measurement Specification, First Cut.

flecting constant-gain antenna characteristics. The curves could be carried flat down to 2 kHz without any change in hardware other than RF filters. At least 16 dB of margin is provided above the system noise floor. With the present RS03 limit of 1 volt/meter, there is up to 90 dB of spread between the new emission limits and the old susceptibility limits. System EMC prediction methods also being studied on this program should permit a realistic rise in the new emission limits to further increase the margin.

(d) Dynamic Range

When impulses are handled by wideband amplifiers, care must be taken that saturation does not occur. The dynamic range of the hypothetical Broadband Measurement System is limited by the output drive capability of the RF amplifiers as summarized in Table 8. The Maximum CW Input is the Overload Point minus the Gain. The Maximum Impulse Input is the Maximum CW Input minus 20 $\log_{10}$(Bandwidth).

The CW Dynamic Range for the broadband system can be obtained by subtracting the Corrected CW Sensitivity from Table 7 from the CW Maximum Input in Table 8. The results are listed in Table 9.

The impulse dynamic range can be obtained by adding r in dB (20 dB for the hypothetical system) to the Corrected CW Sensitivity to obtain the Corresponding Impulse Sensitivity, and subtracting from the Maximum Impulse Input in Table 8. The results are also listed in Table 9.

Unfortunately, the Impulse Dynamic Ranges are negative for the hypothetical Broadband Measurement System for all but Band 1. Even for Band 1, the impulse dynamic range is not sufficient to meet the hypothetical first-cut Broadband Measurement Specification of Figure 6. (It would have to be at least 18 dB).

Table 8. Maximum Amplifier Input Levels

Band	Frequency	Gain	Overload Point (1 dB Compression)	Bandwidth	Maximum Input CW	Maximum Input Impulse
1	14 kHz-100 MHz	55 dB	+29 dBm	100 MHz	81 dBμV	41 dBμV/MHz
2	100-1000 MHz	58	+23	900	72	13
3	1-4 GHz	57	+15	3 GHz	65	-5
4	4-7 GHz	55	+20	3	72	2
5	7-10 GHz	58	+13	3	62	-8

Table 9.

Band	Frequency	Corrected CW Sensitivity	Corresponding Impulse Sensitivity	Dynamic Range CW	Dynamic Range Impulse
1	14 kHz-100 MHz	6.0 dBμV	26.0 dBμV/MHz	75.0 dB	15.0 dB
2	100-1000 MHz	6.1	26.1	65.9	-13.1
3	1-4 GHz	-5.9	14.1	70.9	-19.1
4	4-7	-5.9	14.1	77.9	-12.1
5	7-10	-4.4	15.6	66.4	-23.6

What has happened is that the pre-detection/post-detection bandwidth ratios have become so large that the RF amplifiers saturate on input impulses before the detected output impulses rise above noise. Some feeling for the magnitude of the problem can be obtained by noting that if impulses at the Hypothetical New Broadband Limit of 60 dBμV/m/MHz at 300 MHz in Figure 6, are to be measured with a 900 MHz input bandwidth, the amplifier input (or antenna output) will be 108.1 dBμV. The 58 dB amplifier gain brings this to 166.1 dBμV at the amplifier output (or detector input). In a 50-ohm system, this is 0.8 kilowatt!

Reducing amplifier gain and raising the hypothetical specification limits to compensate does not help significantly. As long as the broadband limit is numerically 20 dB higher than the narrowband limit, the peak power requirements to handle impulses in gigahertz-type input bandwidths remain essentially unchanged.

4.0 WORK PLANNED FOR THE THIRD QUARTER

The work in the second quarter has shown the feasiblity of using IEMCAP in its present state as an integral tool in the EMI/EMC test program of a system. IEMCAP presently has limitations in the areas of frequency range, geometries and signal processing. However, IEMCAP is in the constant state of expansion and improvement because of work being performed under other contracts. This related IEMCAP work is being performed under United States Air Force Contracts at Atlantic Research Corporation. The contract numbers are listed in Section 2 of this report. It is planned to remain tuned in to the various changes that occur in IEMCAP so that where they apply to the goals of this project they may be evaluated.

It has been shown that a broadband measurement system using off-the-shelf components can be assembled with the capability of covering the 14 kHz to 10 GHz frequency range in only five bands. Although the primary thrust has been toward radiated measurements, the system is also applicable to conducted measurements. Sensitivity to narrowband emissions has been shown to the adequate to meet the existing RE02 limits. Sensitivity to broadband emissions, while adequate to also meet RE02 limits, is overshadowed by the possibility of saturation preventing any output indication if truly broadband signals approaching worst-case impulse characteristics are encountered. Work during the next period will concentrate on means to make measurements with a broadband system on broadband interference without danger of saturation obscuring the results. Some approaches to be considered are use of several detectors in series with progressively smaller bandwidths between them, the breaking up of the 5 bands into subbands for parallel analysis and progressive detection with parallel low-level and high-level channels.

In addition an effort will be made to expand the effort to frequencies above 10 GHz. Evaluation of measurement techniques and instrumentation up to 100 GHz shall be performed. Across the entire frequency range of interest an evaluation will be made of state-of-the-art automated EMI/EMC measurement systems.

Analysis of MIL-STD-461 limits will be made and compared to the capability of IEMCAP and the broadband measurement techniques to produce meaningful EMI/EMC data. As part of this effort the MIL-STD-461 limits will be reviewd for meaningful data production. A list of tests for system testing in a priority sequence based on value of data produced will be performed. Supporting information for the listing will also be presented.

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